GEWEX science plan: Addressing the challenges in understanding and predicting changes to water availability in the coming decades

Prepared by Graeme Stephens, Jan Polcher, Xubin Zeng, Peter van Oevelen and the GEWEX SSG

1 General context.

Water is essential for life on Earth and the sustainable management of our water resources in a changing climate increasingly looms as an imperative for the coming century. Today, management of water resources already faces formidable challenges arising from both the expected increased demands from population growth and the sustained economic development in the coming century as well as the increased vulnerability of our freshwater resources globally from over-abstraction, pollution and changing distributions of water supply. Environmental change adds additional pressures on our precious freshwater resources and anthropogenic influences are changing land and water systems, redefining the state of drainage basins and the rivers, lakes and groundwater that supply the bulk of renewable freshwater to society. Widespread changes to our landscape as a result of land-use changes associated with population increases, urbanization, agriculture and industrialization are changing hydrological systems in complex ways, and for many of the world's major rivers, water management is changing the flows, often with severe effects on downstream users, aquatic ecosystems and freshwater discharges to the world's seas and oceans.

Superimposed on these different challenges are the lingering and sustained influences of the increasing levels of greenhouse gasses concentrations that are changing Earth's climate. It is the coupling between water and Earth's energy balance that fundamentally shapes Earth system feedbacks that in turn determine how the climate is changing and its ultimate influence on Earth's fresh water supplies. The projected climate change along with effects of climate variability combine to create extreme and perhaps unprecedented conditions which have high impact for human populations, economic assets and critical physical infrastructure and our natural environment. Hydrological extremes, which are triggered by e.g. extreme rainfall or lack of precipitation and amplified by land surface processes, are the natural disasters which claim the most lives and cause the most damage to infrastructures.

Among the WCRP Core Projects, global and regional water and energy cycles have always been the focus of GEWEX. They are also coupled with the carbon cycle. To address the above challenge, anthropogenic impacts on the water cycle will be emphasized. GEWEX goals and strategic activities will be discussed in Sections 2 and 3, and relations to planned WCRP activities will be presented in Section 4. Opportunities in the next decade will be discussed in Section 5, with expected outcomes provided in Section 6.

2 GEWEX Science Goals.

In recognition of the emerging challenges in understanding how the water cycle is changing in response to these different pressures, and in an attempt to make progress in addressing the issues central to them, GEWEX proposes a focus around three overarching goals. One goal is centrally focused on prediction, another with the critical

coupled interactions that define the physical system and the third delves into anthropogenic influence on the water cycle especially in relation to water resources on the continental and regional scale.

Goal # 1 (GS1): Determine the extent to which Earth's water cycle can be predicted. This Goal is framed around making quantitative progress on three related areas posed in terms of the following questions:

> **1) Reservoirs:** What is the rate of expansion of the fast reservoirs (atmosphere and land surfaces), what is its spatial character, what factors determine this and to what extent are these changes predictable?
>
> **2) Flux exchanges**: To what extent are the fluxes of water between Earth's main reservoirs changing and can these changes be predicted and if so on what time/space scale?
>
> **3) Precipitation Extremes:** How will local rainfall and its extremes change under climate change across the regions of the world?

Goal # 2 (GS2): Quantify the inter-relationships between Earth's energy, water and carbon cycles to advance our understanding of the system and our ability to predict it across scales:

> **1) Forcing-feedback understanding**: How can we improve the understanding of climate forcings and feedbacks formed by energy, water and carbon exchanges?
>
> **2) ABL process representation**: To what extent are the properties of the atmospheric boundary layer (ABL) defined by sensible and latent energy and water exchanges at the Earth's surface versus within the atmosphere (i.e., horizontal advection and ABL-free atmosphere exchanges)?
>
> **3) Understanding Circulation controls:** To what extent are exchanges between water, energy and carbon determined by the large-scale circulations of the atmosphere and oceans?
>
> **4) Land-atmosphere interactions**: How can we improve the understanding of the role of land surface-atmospheric interactions in the water, energy and carbon budgets across spatiotemporal scales?

Goal # 3 (GS3): Quantify anthropogenic influences on the water cycle and our ability to understand and predict changes to Earth's water cycle.

> **1) Anthropogenic forcing of continental scale water availability**: To what extent has the changing greenhouse effect modified the water cycle over different regions and continents?
>
> **2) Water management influences:** To what extent do water management practices and land use change (e.g., deforestation) modify the water cycle on regional to global scales?
>
> **3) Variability and trends of water availability:** How do water & land use and climate change affect the variability (including extremes) of the regional and continental water cycle?

3 Strategic activities.

A number of discrete activities under each goal represent a tangible path forward for addressing these GEWEX goals. Progress under these tasks requires the exploitation of improved data sets of precipitation, river discharge, soil moisture, evapotranspiration, snowpack, and related variables such as water storage, vegetation, land use change data, among other information. This information is to be synchronized with advances in Earth system modeling across scales to advance the development of an integrated analysis of the water and energy exchanges within and between the atmospheric and

continental reservoirs. The coupling of the energy and water cycles with the carbon cycle is also explicitly included, for the first time, in the GEWEX goals (i.e., Goal #2). Together, these are steps required to improve our ability to predict changes to Earth's water cycle and will provide the tools to help close the water budget over land, provide improved information for products related to water availability and quality for decision makers and for initializing and assessing climate predictions across multiple time scales. Detecting and attributing past changes to the water cycle to either changing greenhouse gasses or land and water usage will be essential to increase our confidence in our understanding of prediction tools.

GS1 (i) Document, quantify and explain space/time changes to Earth's hydrological cycle, expressed by atmospheric and surface hydrological properties and the processes that shape these changes. This includes water vapor, clouds, soil moisture, snowpack, fluxes of water at the land and ocean surface (P, ET, Runoff, Sublimation, etc), transports within the atmosphere, and water transport in the land system as a way of quantifying exchanges of water between Earth's water reservoirs with uncertainty characterizations. A crucial task would be to close the water balance at a regional scale. For instance, for the Amazon or Mississippi River basin, to what degree can we close the balance in terms of the mean seasonal cycle? To what degree can we close the balance in terms of the interannual variability and trends?

(ii) Provide global assessments of the weather features that shape rainfall and snowfall, including extremes and assess the representation of these processes in models used to predict and project precipitation and its extremes. Specifically, a focus on identification and reduction of model systematic errors in precipitation, including on daily and sub daily time scales is proposed. This task would then link to improving our understanding of processes and predictive skills at the catchment level and in particular droughts and floods. Here comprehensive and synergistic analysis of observational data and global and regional high-resolution simulations will be needed.

GS2: (i) Characterize the properties of the atmospheric boundary layer (ABL) and advance our quantitative understanding of the ways the ABL influences Earth's climate system. GEWEX would provide a synthesis of information that offers a global characterization of the diurnal cycle of the boundary layer, including its space/time variability, its dependence on land surface dynamics (e.g., in soil moisture and temperature, snowpack, vegetation) and heterogeneity (e.g., in topography, natural and anthropogenic land-water contrast, soil moisture and temperature) and the extent that the ABL is defined by land atmosphere exchange processes of water and energy. This knowledge serves as a basis for assessing the representation of the diurnal cycle of the ABL in models and the representation of processes that influence the ABL.

(ii) Provide a synthesis of Earth's energy and water budget, globally, regionally and over varying time scales. This also includes making advances to methods that can provide quantitative estimates of the Earth's global energy and water imbalance. At regional scale (e.g., for the Amazon or Mississippi River basin), we need to close the energy and water balance in terms of the mean seasonal cycle, inter-annual variability, and trends.

(iii) Advance our understanding of the interactions between water, energy and carbon with focus on critical Earth system feedbacks, including water vapor feedbacks, cloud feedbacks, precipitation-related feedbacks and surface-related feedbacks (e.g., snow albedo feedbacks, vegetation related feedbacks). This will also include a focus on critical aspects of climate forcing with special attention to aerosol influences on cloud and precipitation processes. The role of the large-scale circulations of the atmosphere and oceans in shaping these interactions will be central element of these efforts.

GS3: (i) Attribute observed changes of the continental water cycle to climate change and water and land management. These modifications have been ongoing at the large scale for over a century and their importance has been recognized more widely in recent years We need to develop the expertise to assess the sustainability of man's water and land management in a changing climate. We also need to:

- quantify the effects of water withdrawals and usage (including reservoirs and dams) on the freshwater flows into the oceans, the effects of water withdrawal and land use change on river discharge within climate variability,
- quantify effects of irrigation and urbanization on the dynamics of the ABL and its diurnal cycle in particular, and
- quantify water cycle extremes (e.g., drought, flooding) in a managed environment and develop predictive tools which will allow to better inform society in its efforts to build sustainable and resilient infrastructures.

(ii) Evaluate the contribution of groundwater and subsurface processes to land/atmosphere exchanges and over longer periods on the global water imbalance and sea level.

(iii) Quantify declines in cryospheric reservoirs and changes in snow seasons and melting glaciers. The reduction of water stored on land in a frozen state will modify the timing and volume of water resources which can threaten the sustainability of some hydrological infrastructures.

4 Relation to the WCRP strategic plan and the Lighthouse Activities (LHAs).

The Lighthouse Activities (LHAs, Figure 1) of the WCRP are meant to provide a framework for activities that cut across existing disciplinary driven structure. This should facilitate the exchange between core projects and enable WCRP as a whole to more efficiently address the challenges society faces in a changing climate. Because Earth's water cycle is both central to and integrative of most topics addressed by the WCRP, the activities of GEWEX are expected to be core to most LHA's.

1. *Digital Earths*: To develop a digital and dynamic representation of the Earth system, optimally blending models and observations, to enable an exploration of past, present, and possible futures of the Earth system. This LHA will integrate the impact of human land and water management systems which interact with the weather and climate processes. GEWEX will contribute its model development capabilities and the regional expertise we have built through the regional hydroclimate projects organized over the decades.

2. *Explaining and predicting Earth System Change*: To design, and take major steps toward delivery of, an integrated capability for quantitative observation, explanation, early warning, and prediction of Earth System Change on global and regional scales, with a focus on multi-annual to decadal timescales. GEWEX's contribution will focus on the processes linked to latent and sensible energy exchanges in the atmospheric and continental reservoirs.

3. *Safe Landing Climates*: To explore the routes to climate-safe landing 'spaces' for human and natural systems, on multi-decadal to centennial timescales; to connect climate, Earth system, and socio-economic sciences; to explore present-to-future "pathways" for the achievement of key United Nations Sustainable Development Goals. Water, as emphasized by GEWEX, is societies' most precious resource which needs to be manageable and sustainable in a future climate to ensure a safe landing space. The inclusion of the energy and water cycle coupling with the carbon cycle in the Goal #2 of GEWEX also represents GEWEX's contribution to this LHA.

4   *My Climate Risk*: To develop a new framework for assessing and explaining regional climate risk to deliver climate information that is meaningful at the local and regional scale. Water is not only a geophysical variable but also an essential element of societal and economic importance. It is only at the regional scale where these interactions can be understood and our predictions of the global changes translated into relevant information. GEWEX has already brought together the scientific community around trans-disciplinary research projects in some of the regions and will be available for the objectives of this LHA.

5   *WCRP Academy:* To establish one or more targeted capacity exchange climate programmes, working with one or more of the other lighthouses and established climate education providers, including universities. GEWEX has developed communities and networks that can directly benefit from the training made available through the WCRP Academy. In addition GEWEX community itself develops and organizes training, workshop, summer schools that can be made available to the WCRP Academy.
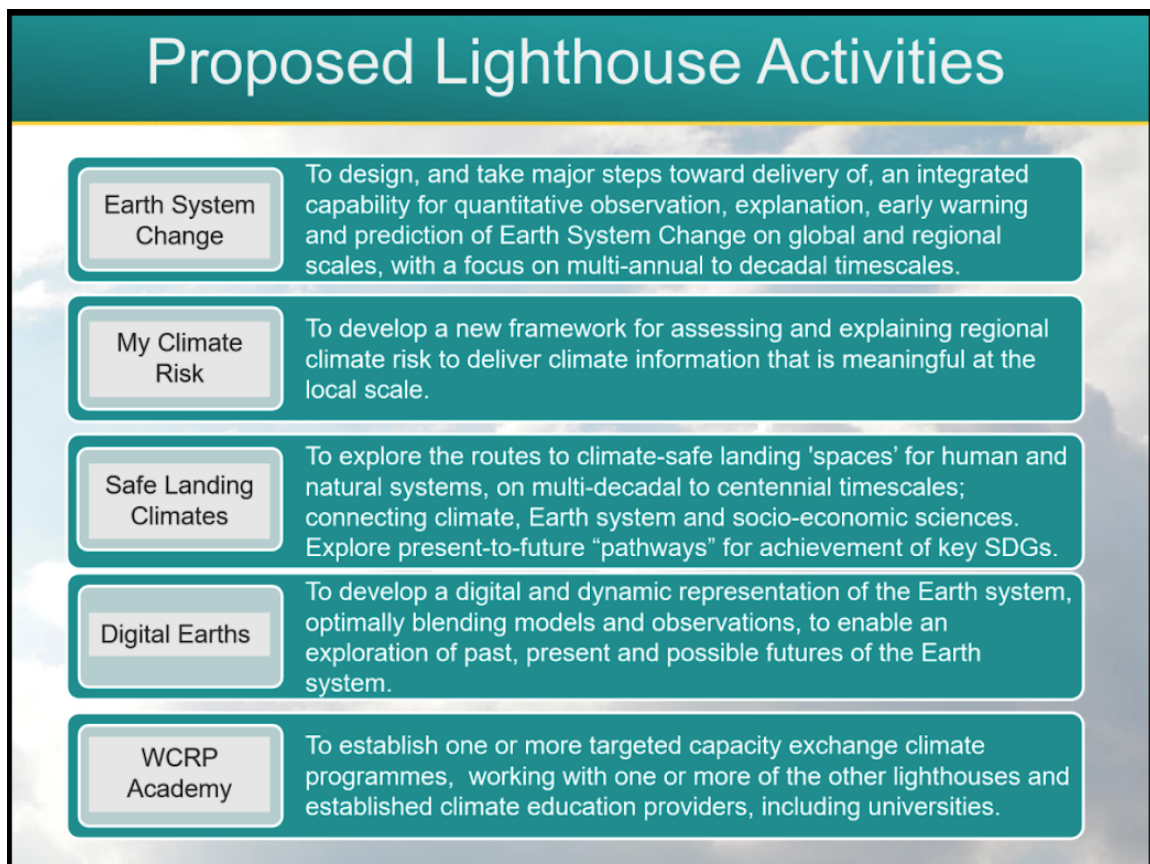
Proposed Lighthouse Activities

Earth System Change	To design, and take major steps toward delivery of, an integrated capability for quantitative observation, explanation, early warning and prediction of Earth System Change on global and regional scales, with a focus on multi-annual to decadal timescales.
My Climate Risk	To develop a new framework for assessing and explaining regional climate risk to deliver climate information that is meaningful at the local scale.
Safe Landing Climates	To explore the routes to climate-safe landing 'spaces' for human and natural systems, on multi-decadal to centennial timescales; connecting climate, Earth system and socio-economic sciences. Explore present-to-future "pathways" for achievement of key SDGs.
Digital Earths	To develop a digital and dynamic representation of the Earth system, optimally blending models and observations, to enable an exploration of past, present and possible futures of the Earth system.
WCRP Academy	To establish one or more targeted capacity exchange climate programmes, working with one or more of the other lighthouses and established climate education providers, including universities.

Figure 1. Objectives of WCRP Lighthouse Activities (LHAs).

5 Opportunities (TBD).

We can anticipate progress over the next 5-10 years because of major opportunities in observations, computing, modeling, artificial intelligence and machine learning (AI/ML), and partnerships.

New observations (in-situ and from space) will reveal new or incomplete understanding of processes in Earth energy and water cycles. This will come from the expansion of the Earth observing systems, including Sentinels (ESA), NASA's designated observables (DO), sustained and enhanced Programs of Records (including ISCCP-NG) as well as

lidar techniques which allow to capture the 3D fields of turbulence and transported scalars. The development of smallsats and cubesats, drones and other space and airborne platforms has opened a whole new era of observational capabilities which should be embedded in the more traditional approaches.

Prolongation of existing observations will reveal new trends and expose unforeseen evolution of the system which will force us to revisit our assumptions and reexamine the contributions of the various man-made changes to the energy and water cycles. The longer time series will also progressively reveal the human responses to changing water resources.

Evolving modeling techniques and exascale computers will enable research and operational simulations at kilometric scales globally and at even higher resolutions regionally. This will reveal that some assumptions made for coarser resolutions are not valid anymore (convection parameterization, neglect of hill-slope processes) and need to be revisited. Over continents these resolutions will reveal that human management of the environment impacts surface/atmosphere interactions and will thus need to be explicitly represented in order to gain the full value for society of (sub)kilometric scale predictions.

Our enhanced observational capabilities and spatially refined models will require new techniques to be confronted and merged in order to access unobservable parameters in the system or determine the state or reservoirs not easily accessible through with the current observational systems. With the rapid progress in AI/ML, their applications become more important for GEWEX activities in the physics-inspired AI/ML analysis of huge amount of data from observations and model output, in the AI/ML integration with modeling (e.g., to replace some of the existing physical parameterizations in Earth system models), and in the AI/ML assistance in data-based scientific discovery and understanding.

The close collaboration of the research groups within GEWEX with operational weather and hydrological services allows to better formulate societal needs in terms of environmental monitoring and prediction and ensures that scientific topics proposed serve a wiser management of the environment and an adaptation to changing resources. The collaboration of GEWEX with iLEAPS and other programs allow us to better understand and model the coupling of the energy and water cycle with the carbon cycle - that becomes crucial for the climate change at decadal to centennial time scales.

6 Expected outcomes and beneficiaries.

Integrated observation-based datasets of all elements of the water, energy and carbon cycle at global and regional scales that can better close the water, energy, and carbon balances than currently available. This will be the basis for our understanding, model evaluation and improvement, climate assessment, and education and capacity building.

Better atmospheric models with scale-aware parameterizations from ~100 km to ~1 km, and better land models including the treatment of human activities (e.g., reservoirs, dams, irrigation sytems) and lateral water movements that are not or do not need to be adequately represented at today's resolutions. These models and observations will serve to detect and attribute trends in the water cycle and thus build the confidence in our understanding of processes. They will also be the basis for prediction and projection at different time scales, for risk assessment and scenario planning via sensitivity tests, and for education and capacity building.

Better understanding processes related to the water and energy cycles as well as their coupling with the carbon cycle through observational data analyses, modeling, and theoretical analyses. This will help improve models and improve the observation-model integration for better observation-based datasets. This will also be the basis for education and capacity building.

Developing knowledge and tools which will allow society to plan and adapt to future climate change and ensure that the impact of hydrological extremes become less destructive. This challenge needs to be addressed by both ends: the development of our geophyscial understanding as exposed above but also our knowledge of the interactions of society with a fluctuating and trending water energy, and carbon cycles.